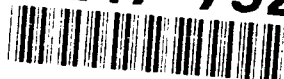




**UNIVERSITY OF NOTRE DAME**  
*Aerospace and Mechanical Engineering*

ERT CENTER FOR  
SPACE RESEARCH

**AD-A247 792**



Date: September 28, 1991  
Prepared by: Dr. F. O. Thomas

Dr. S. G. Lekoudis  
Director, Mechanics Division  
Department of the Navy  
Office of Naval Research  
Code 1132-F  
800 North Quincy Street  
Arlington, Virginia 22217

Subject: End-of-the-Fiscal-Year letter for the period 1 October 1990 to  
30 September 1991, Contract Number N00014-88-K-0670,  
Experimental Investigation of Turbulence Behavior in Shock  
Wave /Turbulent Boundary Layer Interactions

Dear Sir:

The primary objective of this research is to enhance our understanding of the flow field physics associated with shock wave/turbulent boundary layer interactions and thereby enable more accurate predictive models to be developed. It is widely recognized that shock wave/turbulent boundary layer interactions are very important in a variety of high speed aerodynamic applications and yet, despite much attention to this topic in the past, the dynamic mechanisms involved remain poorly understood. The compression ramp generated shock wave/turbulent boundary layer interaction is experimentally investigated in this study. It is a primary objective of this research to isolate the mechanism(s) responsible for the amplification of turbulent stresses through the shock. The interplay between the combined effects of bulk compression, concave curvature, "direct" amplification and pressure gradient will be clarified. In addition, the dynamic mechanism(s) responsible for shock wave oscillation and the role this oscillation plays in the turbulent stress amplification through the shock will also be examined. Measurements documenting the mechanism of turbulent stress relaxation downstream of shock are also obtained.

NOTRE DAME,  
INDIANA 46556

219/219 7007  
AA 219/219 8355

**92-06619**



I. EXPERIMENTAL MEASUREMENT OF NONLINEAR TRANSFER  
FUNCTIONS AND WAVENUMBER -FREQUENCY SPECTRA  
CHARACTERIZING SHOCK WAVE/ TURBULENT BOUNDARY  
LAYER INTERACTIONS

a. Description of Research

A novel area of investigation involves the experimental determination of the nonlinear transfer function characterizing the dynamic mechanisms of energy exchange between spatial scales involved in the shock wave/turbulent boundary layer interaction. This method involves an experimental procedure for determining the linear and quadratically nonlinear relationship between fluctuations monitored at two points in space and time in a turbulent flow field. In this case we seek to model the shock-turbulent flow interaction dynamics by experimental estimation of linear and quadratically nonlinear system elements based upon either measured velocity or wall pressure fluctuation signals obtained at two streamwise locations within the shock interaction region. The attractiveness of this method lies in the fact that it is capable of providing quantitative information regarding the dynamic mechanisms of spectral energy redistribution which characterize the shock wave/turbulent boundary layer interaction and thereby provides unique insight into the physics of the interaction. The dispersion relation will also be experimentally obtained from time-series fluctuation data which provides the capability of relating information regarding energy transfer in terms of temporal frequency to corresponding wavenumber space. This provides a more direct interpretation of data in terms of the physics of the flow.

b. Significant Results Since 1 October 1990

Progress since 10/1/90 involves the following items: (1) The techniques for the acquisition of high quality supersonic hot-wire velocity fluctuation data as required for the experimental estimation of nonlinear system transfer functions have been developed and fully tested. (2) The required two-point supersonic hot-wire data have been acquired in the Notre Dame blow down compressible shear layer facility. This facility was designed and built specifically for the ONR project. These data have been acquired at streamwise locations throughout the shock/boundary layer interaction region and are in the final stages of being processed on the Masscomp 5550 system. This data analysis process is near completion and the results of this phase of the investigation are now being made ready for publication in peer reviewed journals.

### c. Plans for Next Year's Research

Publication of the research results in peer review journals will be the primary objective for the upcoming year.

## II. EXPERIMENTAL INVESTIGATION OF WALL PRESSURE FLUCTUATIONS AND SHOCK WAVE OSCILLATION

### a. Description of Research

One particular aspect of the shock/turbulent boundary layer interaction that remains poorly understood is the large-scale oscillation of the shock front. Here the term "large-scale" refers to the fact that the spatial excursion of the shock typically may extend a significant fraction of the local boundary layer thickness. This oscillation is of much interest because it can significantly affect the local aerodynamic loading of aircraft structures as well as local heat transfer rates. In addition, it is well known that the shock oscillation provides an important mechanism for the amplification of turbulent stresses through the interaction. In this portion of the research the mechanism responsible for the shock wave oscillation in compression ramp shock/boundary layer interactions will be clarified. In particular, it is to be determined whether feedback from low frequency oscillations within the separation bubble or coherent vortical structures in the approaching boundary layer or a combination of both drive the shock unsteadiness. This will be accomplished by detailed wall surface pressure measurements which are to be obtained both upstream and throughout the shock interaction region. Novel digital signal processing techniques will be utilized in the analysis of the instantaneous wall pressure time-series data.

### b. Significant Results since 1 October 1990

Progress since 10/1/90 involves the following items: (1) Completion of data analysis from a major series of experiments that were performed in the in-draft supersonic facility. This involved the analysis of wall pressure fluctuations which characterize the shock/turbulent boundary layer interaction for several compression ramp angles (i.e. several interaction strengths). These experiments involved shock /turbulent boundary layer interactions both with and without large-scale flow separation. In this manner the role of the separation bubble on shock oscillation has been clearly documented. In addition, measurements conditioned to the upstream boundary layer burst-sweep cycle of events have allowed the assessment of the role of the bursting process upon shock oscillation. (2) Complimenting the investigation of the dynamic mechanisms of shock oscillation, both the nonlinear transfer function and



OFFICE OF NAVAL RESEARCH  
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT  
1 October 1990 through 30 September 1991

R&T Number:

Contract/Grant Title: N00014-88-K-0670, Experimental Investigation of Turbulence  
Behavior in Shock Wave/Turbulent Boundary Layer Interactions  
Scientific Officer: Dr. S. G. Lekoudis

Principal Investigator: Dr. F. O. Thomas

Mailing Address: Aerospace and Mechanical Engineering  
University of Notre Dame, Notre Dame IN 46556  
Phone Number: (219 ) 239-7899

FAX Number: ( 219 ) 239-8355

E-Mail Address: none

a. Number of Papers Submitted to Referred Journal but not yet published:	<u>4</u>
b. Number of Papers Published in Referred Journals: (List Attached):	<u>2</u>
c. Number of Books or Chapters Submitted but not yet Published:	<u>0</u>
d. Number of Books or Chapters Published (List Attached):	<u>1</u>
e. Number of Printed Technical Reports & Non-Referred Papers (List Attached):	<u>6</u>
f. Number of Patents Filed:	<u>0</u>
g. Number of Patents Granted (List Attached):	<u>0</u>
h. Number of Invited Presentations at Workshops or Professional Society Meeting (List Attached):	<u>1</u>
i. Number of Presentations at Workshops or Professional Society Meetings (List Attached):	<u>8</u>
j. Honors/Awards/Prizes for Contract/Grant Employees: (List Attached, may include Society Awards/Offices, Promotions, Faculty Awards/Offices, etc.)	<u>2</u>

k. Providing the following information will assist with statistical purposes.

PI/CO-PI:	TOTAL	<u>1</u>	Grad Students:**	TOTAL	<u>3</u>
	Female	<u>0</u>		Female	<u>0</u>
	Minority*	<u>0</u>		Minority*	<u>0</u>

Post Doc:**	TOTAL	<u>0</u>
	Female	<u>0</u>
	Minority*	<u>0</u>

1. Degrees Granted (List Attached):	<u>3</u>
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\* Underrepresented or minority groups include Blacks, Hispanics, and Native Americans.

Asians are not considered an underrepresented or minority group in science and engineering.

\*\* Supported at least 25% this year on contract/grant.

Enclosure(1)

Enclosure (2)  
List of Publications/Reports/Patents/Graduates

1. Papers Published in Referred Journals

"Experimental Investigation of the Nonlinear Spectral Dynamics of Planar Jet Transition," with H. C. Chu, Phys. of Fluids A, 3, 6, pp. 1544-1559, 1991.

"On the Structure of Mixing Layers and Jets," Journal of Applied Mechanics Reviews, 44, 3, pp. 119-153, 1991.

(4 others have been submitted for publication, 4 are currently in preparation)

2. Books (and sections thereof) Published:

"Experimental Determination of Nonlinear Transfer Functions Characterizing Shock Wave/Turbulent Boundary Layer Interactions," with H. C. Chu and C. M. Putnam, Unsteady Aerodynamics, Aeroelasticity, and Aeroacoustics of Turbomachines and Propellers, Springer-Verlag Publishers, In Press.

3. Technical Report, Non-Refereed Papers

"Quantitative Measurement of Spectral Redistribution Characterizing Shock Wave/Turbulent Boundary Layer Interactions," with H. C. Chu and C. M. Putnam, AIAA paper 92-0745.

"Measurement of the Nonlinear Spectral Dynamics Characterizing a Shock Wave/Turbulent Boundary Layer Interaction," with C. Putnam and H. C. Chu, AIAA paper 91-0653.

"Measurement of Nonlinear Wave Coupling and Energy Transfer in Planar Jet Shear Layer Transition," with H. C. Chu, AIAA paper 91-0314.

"On the Nonlinear Spectral Dynamics of Planar Jet Transition," with H. C. Chu, Proceedings of the Twelfth Symposium on Turbulence, University of Missouri-Rolla, 1990.

"An Overview of Compressible Shear Layer Research at the University of Notre Dame," with D. K. Gakio, Proceedings of the 73rd Meeting of the Supersonic Tunnel Association, University of Illinois at Urbana-Champaign, 1990.

"A Summary of Hot-Wire Probe Design, Fabrication and Calibration for Supersonic Flows," with H. C. Chu and T. J. Mueller, Proceedings of the 76th Semi-Annual Meeting of the Supersonic Tunnel Association, Tel Aviv, Israel, 1991.

4. **Presentations**

a. **Invited Lectures**

Thomas, F. O., "On the Nonlinear Spectral Dynamics of Jet Transition", invited lecture presented at NASA Lewis Research Center, Cleveland Ohio, 1990.

b. **Contributed**

"Experimental Determination of Nonlinear Transfer Functions Characterizing Shock Wave/Turbulent Boundary Layer Interactions," with H. C. Chu and C. M. Putnam, presented at the IUTAM Sixth International Symposium on Unsteady Aerodynamics, Aeroelasticity, and Aeroacoustics of Turbomachines and Propellers, University of Notre Dame, Notre Dame, IN, 1991.

"A Summary of Hot-Wire Probe Design, Fabrication and Calibration for Supersonic Flows," with H. C. Chu and T. J. Mueller, presented at the 76th Semi-Annual Meeting of the Supersonic Tunnel Association, Tel Aviv, Israel, 1991.

"Quantitative Measurement of Spectral Redistribution Characterizing Shock Wave/Turbulent Boundary Layer Interactions," with H. C. Chu and C. M. Putnam, to be presented at the 30th AIAA Aerospace Sciences Meeting, 1992.

"Measurement of the Nonlinear Spectral Dynamics Characterizing a Shock Wave/Turbulent Boundary Layer Interaction," presented at the 29th AIAA Aerospace Sciences Meeting, 1991.

"Measurement of Nonlinear Wave Coupling and Energy Transfer in Planar Jet Shear Layer Transition," presented at the 29th AIAA Aerospace Sciences Meeting, 1991.



"On the Nonlinear Spectral Dynamics of Planar Jet Transition," Presented at the Twelfth Symposium on Turbulence, University of Missouri-Rolla, September 24-26, 1990.

"Nonlinear Spectral Dynamics of Planar Jet Transition," Bulletin of the American Physical Society, 35, (10): 2303, 1990.

"An Overview of Compressible Shear Layer Research at the University of Notre Dame," with D. K. Gakio, Presented at the 73rd Meeting of the Supersonic Tunnel Association, University of Illinois at Urbana-Champaign, March 1990.

5. Patents Granted:

None

6. Degrees Granted

D. K. Gakio	Nov. 1990	M.S.
C. M. Putnam	April 1991	M.S.
H. C. Chu	Dec. 1991	Ph. D.

Enclosure (3)

List of Awards/Honors/Prizes

1. Dr. F. O. Thomas, University of Notre Dame, Notre Dame Aerospace and Mechanical Engineering Faculty Award for excellence in research and teaching, 1990.
2. Dr. F. O. Thomas, University of Notre Dame , promoted to Associate Professor with tenure, May, 1991.

Enclosure (4)

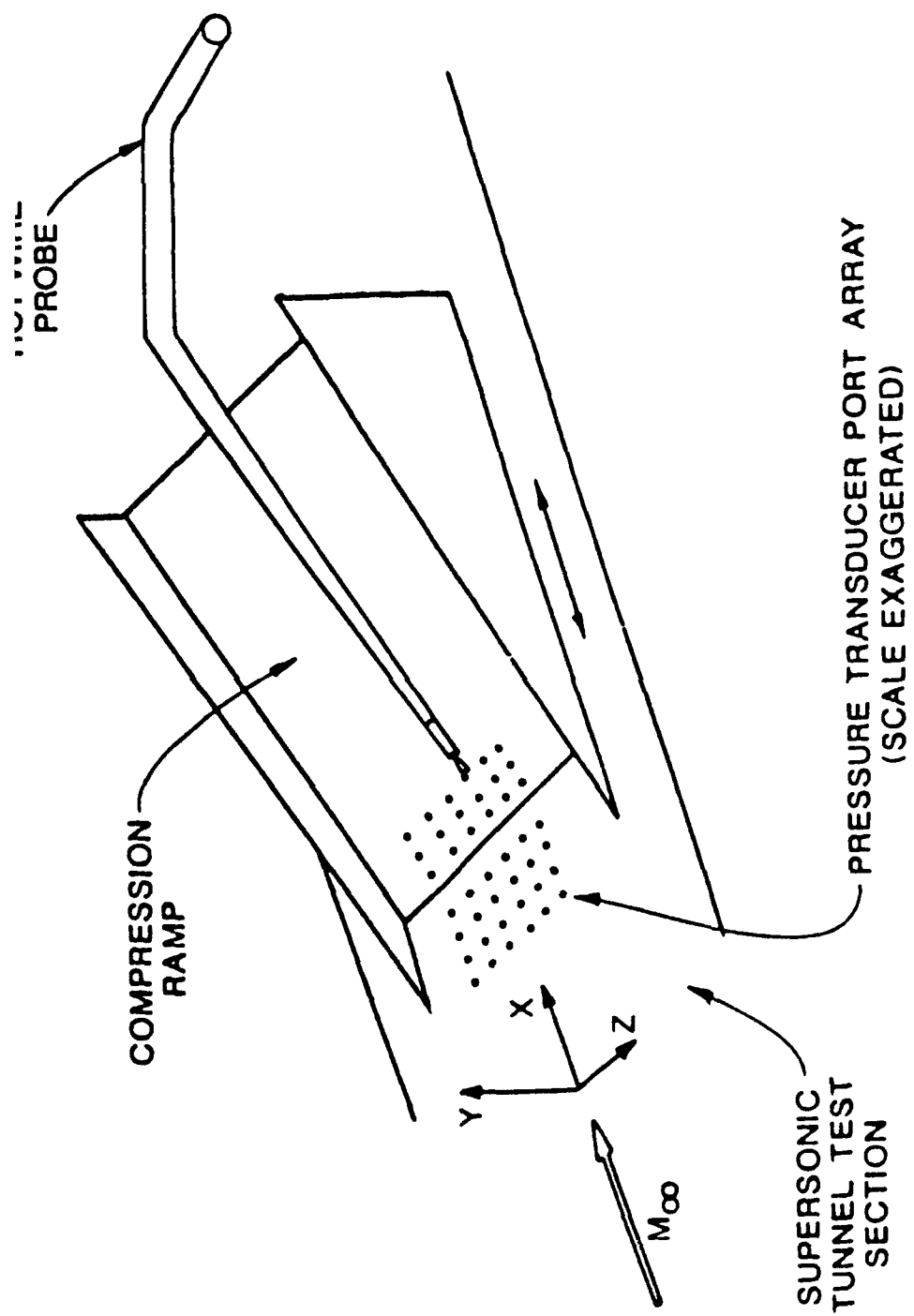
OTHER SPONSORED RESEARCH

None

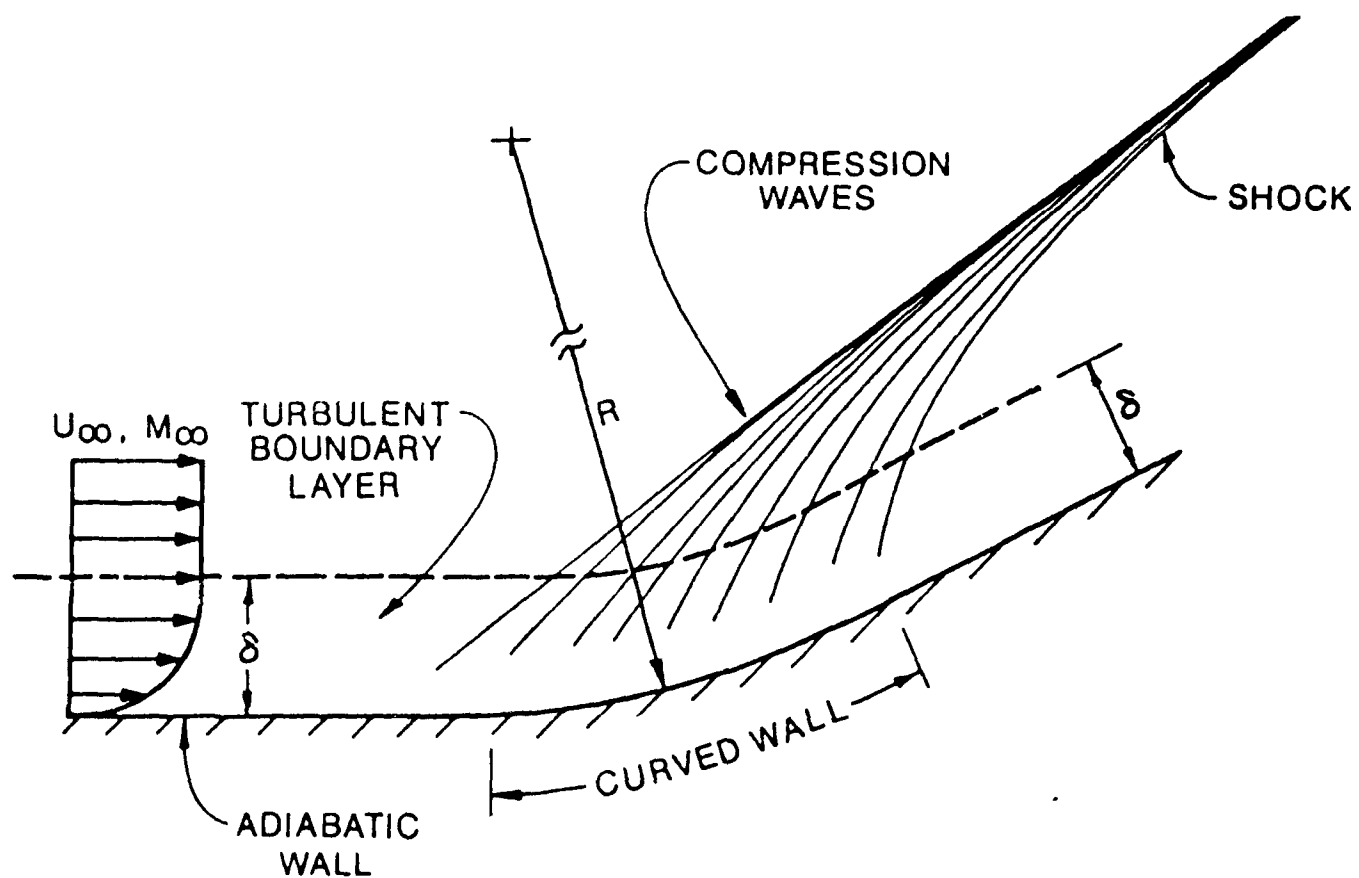
At this time all phases of the project are either on schedule or have been completed.

Sincerely,

Flint O. Thomas, Ph.D.  
Associate Professor, Aerospace and  
Mechanical Engineering



SCHEMATIC OF COMPRESSION RAMP MODEL  
IN SUPERSONIC WIND TUNNEL TEST SECTION



CONCAVE CURVATURE WALL GENERATED SHOCK  
WAVE/TURBULENT BOUNDARY LAYER INTERACTION

FIGURE 2